

# Enabling concentrating solar power in Australia:

An investigation of the benefits and  
potential role of concentrating solar  
power and non-conventional fuel  
hybrid plants in Australia's transition  
to a low-carbon energy future

**Juergen Heinz Martin Peterseim**

Institute for Sustainable Futures

University of Technology, Sydney

**Thesis submitted for the PhD in Sustainable Futures**

**September 2014**



### **STATEMENT OF ORIGINAL AUTHORSHIP**

I certify that the work in this thesis has not previously been submitted for a degree and nor has it been submitted as part of the requirements for a degree.

I also certify that the thesis is an original piece of research written by me, except where noted in the text. Any help that I have received in my research work and in the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of candidate:

Juergen Heinz Martin Peterseim

I dedicate this thesis to love and hope:  
love for my wife Anja and my children Lola and Leon, and  
hope for a bright future for concentrating solar power in Australia.

## ACKNOWLEDGEMENTS

Many people supported me in my research and in my personal life throughout this three-year journey. This includes family, friends, supervisors and colleagues, and it would take too long to thank them all individually. In particular I want to thank my wife Anja and my children Lola and Leon for their support as they provided welcome distractions that took my mind off specific research issues. This gave me time to reconsider and in many cases improve my ideas. I know that during this time I did not always have as much time for my family as I wished, and I want to thank Anja for her understanding and efforts to give me time for my research. Without her support this thesis would not exist.

I want to acknowledge my supervisors Prof. Stuart White, Prof. Udo Hellwig and Dr. Amir Tadros for their continual support, their willingness to help and their optimism. I want to thank Prof. Stuart White for his deep insights into sustainability and energy research. His availability, even at short notice, and his detailed feedback allowed me to solve problems quickly and stay on track. I want to thank Prof. Udo Hellwig, not only for his valuable technical support during my candidature, but also for his mentorship since I entered the energy sector in 2003. I don't think I would be in the position I am in today if it had not been for his support. I also want to thank him for the opportunity to work for him part-time during this research project. This was a significant help for me during my second period of time as a student. Last but certainly not least, I want to thank Dr. Amir Tadros for this for valuable insights into techno-economic modelling. His detailed understanding of power plants in the context of the Australian electricity market was invaluable.

Various people within and outside the university contributed to specific aspects of this research. In particular I want to thank Dr. Deborah O'Connell and Dr. Alexander Herr from CSIRO Ecosystems Sciences, and Sarah Miller from CSIRO Energy Technology, for their contribution to the resource assessment, which is a key component of this work. I also want to thank Frank Klostermann, formerly of Thiess Services Pty. Ltd., for his insights into the industry, and for the financial contribution to the Swanbank case study. I sincerely hope that this proposal will eventually turn into an actual power station. I also want to thank various students and staff at ISF for their friendship, support, insightful discussion and time, which not only helped with the thesis but also contributed to my personal development.

Last but not least I want to thank the University of Technology, Sydney for the confidence they showed in me by awarding me a UTS President's Scholarship and two travel funds. Without the scholarship I would not have been able to do this research and the travel funds allowed me to attend relevant international conferences.

## TABLE OF CONTENTS

Statement of original authorship.....	ii
Acknowledgements.....	iv
Table of contents .....	v
List of Figures .....	viii
List of Tables .....	xi
List of publications .....	xii
List of abbreviations.....	xiv
Abstract.....	xv
Foreword.....	xvii
1 Introduction .....	1
2 Literature review.....	4
2.1    The Australian electricity market .....	4
2.1.1    Current status.....	5
2.1.2    Transition to a low carbon future .....	8
2.2    Concentrating solar power plants .....	13
2.2.1    History and technology development.....	13
2.2.2    Outlook.....	17
2.2.3    Australian market.....	20
2.3    Non-conventional fuels for power generation.....	23
2.3.1    Energy from waste .....	23
2.3.2    Energy from biomass.....	28
2.3.3    Australian market.....	30
2.4    CSP hybrid benefits & challenges .....	34
2.5    CSP hybrid plants.....	38
2.5.1    CSP-Natural gas .....	38
2.5.1.1    Commercial references .....	38
2.5.1.2    Concepts .....	40
2.5.2    CSP-Coal .....	42
2.5.2.1    Commercial references .....	42
2.5.2.2    Concepts .....	43
2.5.3    CSP-non-conventional fuels .....	44
2.5.3.1    Commercial references .....	44
2.5.3.2    Concepts .....	45

2.5.4	CSP-geothermal.....	47
2.6	Introduction to transition management and transition theory .....	49
2.7	Conclusion from the literature review and research gaps .....	55
3	Research design .....	57
3.1	Research questions.....	59
3.2	Methods .....	60
3.2.1	Workshops and interviews.....	60
3.2.1.1	CSP technology selection.....	61
3.2.1.2	Implementation barriers .....	61
3.2.2	Modelling .....	62
3.2.2.1	Techno-economic modelling .....	62
3.2.2.2	GIS modelling.....	63
3.2.3	Multi-criteria decision-making .....	64
3.2.4	Case studies.....	65
3.3	Theoretical framework .....	67
3.4	Research ethics.....	72
4	Results and discussion .....	73
4.1	CSP hybrid categories and energy source combinations .....	73
4.2	CSP-non-conventional fuel potential and plant area identification in Australia..	82
4.3	CSP technology selection.....	97
4.4	Techno-economic optimisation.....	111
4.4.1	Identical steam parameter from CSP and biomass components.....	111
4.4.2	External CSP steam superheating with biomass .....	124
4.4.3	Future CSP–EfB and CSP–EfW hybrid plants .....	135
4.5	Implementation barriers .....	138
4.5.1	Significant Australian barriers to CSP .....	139
4.5.1.1	Social barriers .....	140
4.5.1.2	Technical barriers .....	142
4.5.1.3	Environmental barriers.....	145
4.5.1.4	Economic barriers.....	146
4.5.1.5	Policy barriers .....	148
4.5.2	Rating results.....	151
4.5.2.1	CSP-only plants .....	153
4.5.2.2	CSP hybrid plants.....	154
4.5.2.3	CSP-only versus hybrid rating differences.....	155

4.5.3	Discussion.....	157
4.5.4	Conclusions .....	159
4.6	Case studies .....	160
4.6.1	Swanbank, CSP-multiple feedstock hybrid.....	160
4.6.1.1	SolarPACES 2012 conference paper .....	161
4.6.1.2	Environmental analysis.....	174
4.6.1.3	Hybrid versus CSP-only cost comparison .....	175
4.6.1.4	Socio-economic benefits .....	175
4.6.1.5	Economic and socio-ecological renewal at Swanbank .....	178
4.6.2	Griffith, CSP-single feedstock hybrid.....	180
4.6.2.1	SolarPACES 2013 conference paper .....	181
4.6.2.2	Socio-economic benefits .....	192
4.7	CSP hybrids as a pathway to a low carbon future .....	194
5	Future research .....	206
6	Conclusions .....	209
	References .....	214
	Appendix .....	236



## LIST OF FIGURES

Figure 1: Australia’s electricity generation 2011-12 by energy source (Bureau of Resources and Energy Economics 2013); Other includes oil, bioenergy, solar PV, and multi-fuel fired power plants .....	5
Figure 2: Changes in electricity generation and emissions in the NEM (pitt&sherry 2014)....	6
Figure 3: Changes in electricity generation by fuel type in the NEM (pitt&sherry 2014) .....	6
Figure 4: Australian electricity generation from renewable energy (Bureau of Resources and Energy Economics 2013) .....	7
Figure 5: Electricity price indices for households and businesses, Australia (Bureau of Resources and Energy Economics 2013) .....	8
Figure 6: Australia’s emissions trends, 1990 to 2020 (Department of Climate Change and Energy Efficiency 2012) .....	9
Figure 7: Forecast renewable energy investment – value of construction and capacity added (Macromonitor 2013) .....	11
Figure 8: Share of electricity generation by energy type, prepared with data from Syed (2012) .....	12
Figure 9: Al Meadi pumping station using the five parabolic troughs with direct steam generation (Stinnesbeck 1914) .....	13
Figure 10: One of three solar tower systems of the 392 MWe Ivanpah power station, USA	15
Figure 11: Annual electricity capacities and generation for CSP and PV from 2011-18 (International Energy Agency 2013) .....	17
Figure 12: Tariff and levelised cost of energy development above DNI level; Percentage compared to reference plant in Spain with a DNI of 2,084 kWh/m <sup>2</sup> /a at 100 per cent (AT Kearney & ESTELA 2010) .....	19
Figure 13: CSP project pipeline by technology in per cent of total CSP projects as per 1 <sup>st</sup> March 2013 (SBC Energy Institute 2013) .....	20
Figure 14: Direct normal irradiation for potential global CSP sites (Trieb et al. 2009) .....	21
Figure 15: Energy from waste conversion technologies (Kaltschmitt 1998) .....	23
Figure 16: a: Waste incineration plant Bullerdeich in Hamburg in 1896 (Vehlow 2004) and b: modern Energy from Waste plant in Tokyo, Japan (right) .....	24
Figure 17: Rate of recycling versus incineration with energy recovery of municipal waste, 2005 for the EU (European Environment Agency 2007) .....	25
Figure 18: CSP power top-up (left) or fuel saver (right) option .....	38

Figure 19: a:75 MWe equivalent CSP steam boost to Martin Next Generation power station in the USA (Florida Power & Light Company 2010) and b: 100 MWe Shams One plant (Goebel & Luque 2012) .....	39
Figure 20: a: 228 MWe solar tower ISCC concept (Peterseim et al. 2012c) and b: 4.6 MWe Solugas tower in Spain (Quero et al. 2013).....	41
Figure 21: Kogan Creek Solar Boost project under construction as per October 2013 .....	43
Figure 22: First CSP-biomass hybrid plant in Spain, 22.5 MWe Termosolar Borges, Spain ...	45
Figure 23: Schematic diagram of the hybrid solar-geothermal power plant (Zhou, Doroodchi & Moghtaderi 2013).....	48
Figure 24: Transition management cycle (Loorbach 2010) .....	50
Figure 25: Multi-level perspective (Geels 2002) .....	51
Figure 26: Emerging technical trajectory carried by local projects (Geels & Raven 2006, p. 379) .....	53
Figure 27: Research outline .....	57
Figure 28: Research structure showing the sequence of the research components (black arrows) and the information flow (dotted arrows).....	58
Figure 29: Case study locations in Ipswich, Queensland, and Griffith New South Wales .....	66
Figure 30: Multi-level perspective on transitions (Geels & Schot 2007, p. 401) .....	70
Figure 31: Reconfiguration pathway (Geels & Schot 2007).....	71
Figure 32: Potential efficiency increase (black line) and range of cost impact (red dotted lines) based on future steam parameters for a 100 MWe (net) CSP–EfB hybrid plant with air cooling at Mildura, Australia .....	136
Figure 33: Participant breakdown for implementation barrier ranking .....	139
Figure 34: Barrier rating results for CSP-only (orange) and CSP hybrid plants (green) .....	152
Figure 35: Barrier category ratings for CSP-only plants.....	154
Figure 36: Barrier category ratings for CSP hybrid plants.....	155
Figure 37: Detrimental CSP implementation cycle with intervention option. Adapted from Effendi and Courvisanos (2012) .....	158
Figure 38: Swanbank site with the proposed CSP–EfB and CSP–EfW hybrid plant (CSP = yellow and EfB/EfW = green), the existing coal fired Swanbank B power plant and the existing gas fired Swanbank E power plant (red squares), and landfill (blue polygon) .....	160
Figure 39: Vision for an eco-industrial transition – map and concept, Baumann et al. (2012) .....	178
Figure 40: Potential site for the CSP–EfB hybrid plant near Griffith.....	180

Figure 41: Multi-level perspective for different renewable energy technologies in the Australian electricity generation market; Blue = hydro, grey = wind, green = biomass, yellow = PV, orange = CSP, and red = others; Adapted from Geels & Schott (2007) ..	200
Figure 42: Multi-level perspective for CSP-only and hybrid technologies in the Australian electricity generation market. Adapted from Geels & Schott (2007) .....	201
Figure 43: Possible reconfiguration pathway for the implementation of CSP technologies in the Australian electricity generation market; Red squares = CSP add-ons to existing power plants, green triangles = new CSP hybrid plants, and yellow pentagons = new CSP-only plants. Adapted from Geels & Schott (2007). ....	203
Figure 44: Overlay of DNI (PIRSA Spatial Information Services 2009) with mine sites in Australia (Geoscience Australia 2010) .....	207

## LIST OF TABLES

Table 1: Biomass generation capacity in MWe per state and fuel in 2009 (Stucley et al. 2012) updated with the recently commissioned 36 MWe Mackay plant using bagasse in Queensland (Biomass Power & Thermal Magazine 2011) .....	32
Table 2: Ranking differences between CSP-only and hybrid plants showing total average and group averages for researcher ( $\Delta R$ ), owners/operators ( $\Delta O$ ), consultants ( $\Delta C$ ), technology provider ( $\Delta TP$ ) and government ( $\Delta G$ ).....	156
Table 3: Swanbank power plant cost breakdown and investment distribution.....	177
Table 4: Griffith power plant cost breakdown and investment distribution.....	192

## LIST OF PUBLICATIONS

### Relevant publications:

- Peterseim J.H., Herr, A., Miller, S., White, S., O’Connell, D.A., 2014, Concentrating solar power/alternative fuel hybrid plants: Annual electricity potential and ideal areas in Australia, *Energy*, vol. 68, pp. 698-711.
- Peterseim, J.H., Hellwig, U., Tadros, A., White, S., 2014. Hybridisation optimization of concentrating solar thermal and biomass power generation facilities. *Solar Energy*, vol. 99, 203–214.
- Peterseim, J. H., Tadros, A., Hellwig, U., White, S., 2014. Increasing the efficiency of parabolic trough plants using thermal oil through external superheating with biomass, *Energy Conversion and Management*, vol. 77, pp. 784–793
- Peterseim, J.H., White, S., Tadros, A., Hellwig, U., 2014. Concentrating solar power hybrid plants - enabling cost effective synergies. *Renewable Energy*, vol. 67, pp. 178-185.
- Peterseim, J.H., White, S., Tadros, A., Hellwig, U., 2013. Concentrated solar power hybrid plants, which technologies are best suited for hybridisation? *Renewable Energy*, vol. 57, 520–532.
- Peterseim, J.H., Tadros, A., White, S., Hellwig, U., Landler, J., Galang, K., 2013. Solar tower-biomass hybrid plants – maximizing plant performance. *Energy Procedia*, vol. 49, no. SolarPACES 2013 conference special, pp. 1197–1206
- Peterseim, J.H., Tadros, A., White, S., Hellwig, U., Klostermann, F., 2012. Concentrated solar power / Energy from Waste hybrid plants - creating synergies. In: *SolarPACES Conference*, Marrakech.
- Peterseim, J.H., White, S., Hellwig, U., Tadros, A., Vanz, E., 2012. Pre-feasibility study for a multi-fuel / concentrated solar power hybrid plant at Swanbank, QLD. Prepared for Thiess Services Pty Ltd by the Institute for Sustainable Futures, University of Technology, Sydney, Unpublished report.

#### Other publications:

- Peterseim, J.H., Tadros, A., Hellwig, U., White, S., 2013. Integrated solar combined cycle plants using solar towers with thermal storage to increase plant performance. In: *ASME Power Conference*, Boston.
- Peterseim, J.H., Hellwig, U., Endrullat, K., 2013. Parallel flow boiler designs to minimise erosion and corrosion from dust loaded flue gases. In: *ASME Power Conference*, Boston.
- Rutovitz, J., Peterseim, J., Elliston, B., Harris, S., Mohr, S., Lovegrove, K., Want, A., Langham, E., MacGill, I., 2013. Breaking the solar gridlock. Potential benefits of installing concentrating solar thermal power at constrained locations in the NEM. Prepared for the Australian Solar Thermal Energy Association (AUSTELA) by the Institute for Sustainable Futures, UTS, Sydney.
- Peterseim, J.H., White, S., Tadros, A., Hellwig, U., 2012. Integrated Solar Combined Cycle plants using solar power towers to optimise plant performance. In: *SolarPACES Conference*, Marrakech.
- Peterseim, J.H., Hellwig, U., Guthikonda, M., Widera, P., 2012. Quick start-up auxiliary boiler/heater – optimizing solar thermal plant performance. In: *SolarPACES Conference*, Marrakech.
- Baumann, C., Asker, S., Giurco, D., Peterseim, J.H., White, S., 2012. ECO-INDUSTRIAL TRANSITION' A vision for economic and socio-ecological renewal at Swanbank. Prepared for Thiess Services Pty Ltd by the Institute for Sustainable Futures, University of Technology, Sydney, Australia.
- Peterseim, J.H., 2012. Energy Efficiency Opportunity Assessment at Tarong Power Station. Prepared for the Department of Resources, Energy and Tourism by the Institute for Sustainable Futures, Sydney, Unpublished report.
- Memary, R., Giurco, D., Prior, T.D., Mason, L. M., Mudd, G.M., Peterseim, J.H., 2011. Clean energy and mining - future synergies. In: *Second International Future Mining Conference*. The AusIMM (The Mineral Institute), Sydney, Australia.
- Peterseim, J.H., Hellwig, U., 2011. Water circulation calculation for Concentrated Solar Thermal Plants. In: *SolarPACES Conference*, Granada.

## LIST OF ABBREVIATIONS

AHP	analytical hierarchy process	MLP	multi-level perspective
ASTRI	Australian solar thermal research initiative	MSW	municipal solid waste
AU\$	Australian dollar	MW	megawatt
b	billion	MWh	megawatt hour
CapEx	capital expenditure	MWth	Megawatt thermal
CO <sub>2</sub>	carbon dioxide	NEM	national electricity market
CSP	concentrating solar power	OpEx	operational expenditure
DNI	direct normal irradiance	PPA	power purchase agreement
EfB	energy from biomass	PV	photovoltaic
EfW	energy from waste	R&D	research and development
EPC	engineering, procurement and construction	RDF	refused derived fuels
GIS	geographic information system	RECs	renewable energy certificates
GWh	gigawatt hour	RET	renewable energy target
h	hours	SEGS	solar energy generation systems
HRSG	heat recovery steam generator	SNM	strategic niche management
ISCC	integrated solar combined cycle	SRF	solid recovered fuels
kW	kilowatt	t	tonnes
kWh	kilowatt hour	t/h	tonnes per hour
LCOE	levelised cost of electricity	TES	thermal energy storage
m	million	TWh	terrawatt hour
		US\$	U.S. dollar

## ABSTRACT

After decades of stability the Australian electricity market is undergoing changes. Current government targets aim to reduce greenhouse gas emissions by 5% and raise renewable electricity production to 45 TWh by 2020. In addition, increases to natural gas prices, aging generation assets and falling electricity demand have had an impact in recent years.

Uncertainties exist around current policies, including the carbon pricing mechanism and the renewable energy target, but in light of Australian and international ambitions to lower greenhouse gas emissions the deployment of renewable energy technologies is essential. In recent years wind and photovoltaic installations have shown the highest renewable energy growth rates while concentrating solar power has struggled, despite Australia having some of the best natural resources for concentrating solar power in the world and some selected government funding. Reasons for the slow uptake include the comparatively high cost and lack of financial incentives. While technology costs are expected to decrease by up to 40% by 2020 through deployment as well as research and development, other cost reduction options have to be identified to promote short-term implementation in electricity markets such as Australia where the wholesale cost is low. To overcome the cost problem and to address other relevant implementation barriers this research analyses the hybridisation of concentrating solar power with biomass and waste feedstocks.

The results of this research include:

- a recommendation for a categorisation system for CSP hybrid plants based on the degree of interconnection of the plant components
- the availability of combined resources to generate up to 33.5 TWh per year and abate 27 million tonnes CO<sub>2</sub> annually
- an analysis of the most suitable CSP technologies for hybridisation
- a technology comparison showing CSP cost reductions through hybridisation of up to 40%
- the identification of cost differences of up to 31% between different hybrid concepts
- an analysis showing that the current economic and policy settings are the most significant implementation barriers
- two case studies with different biomass and waste feedstocks requiring power purchase agreements of AU\$ 100-155/MWh.



Based on the various benefits of concentrating solar power hybrid plants, this research analyses the potential role of this technological pairing in Australia's transition to a low carbon energy future. The research concludes that concentrating solar power hybrid plants, not only hybridised with biomass and waste feedstocks, can immediately enable a lower cost deployment of concentrating solar power facilities in Australia. The technology, deployment and operation of the first hybrid installations would provide market participants with valuable lessons and would have the potential to reconfigure the electricity market towards more sustainable generation. This could help promote the development of future low-cost concentrating solar power plants in Australia.

## FOREWORD

When I started considering a PhD candidature in 2010 I already had a few potential topics in mind that derived from observations I had made since entering the energy business in 2003. I worked as an industrial engineer in several areas, including project management and business development, for the German boiler design companies La Mont-Kessel GmbH & Co. KG and ERK Eckrohrkessel GmbH. This allowed me to develop a detailed understanding of current issues with solid, liquid and gaseous fuel fired water tube boiler systems, and of their impact on power plant efficiency, reliability and cost. My early focus was on energy from biomass and from waste systems as well as work on compact boiler and heat exchanger systems. After moving to Australia in 2007 I continued work in these fields but also expanded into heat recovery and natural gas fired boilers.

The good resource for solar energy in Australia, and my interest in Rankine cycle systems, shifted my attention to concentrating solar power. The technology was immediately appealing due to its futuristic appearance, its low carbon intensity, and the availability of mature equipment for most of the plant. In late 2010 I was awarded a UTS scholarship and since commencing this research in March 2011 my interest in concentrating solar power has continued to grow. The work I have done for my PhD has enabled me to expand my knowledge not only through theoretical work, such as a literature review and thermo-economic modelling, but also through the exchange of ideas and cooperation with industry partners, both those I had known previously and others I have met during the last three years.

I sincerely hope that this thesis will contribute to the deployment of concentrating solar power plants in Australia and I am looking forward to further engaging with the technology for the foreseeable future.